Open Heavy Flavor Results from STAR

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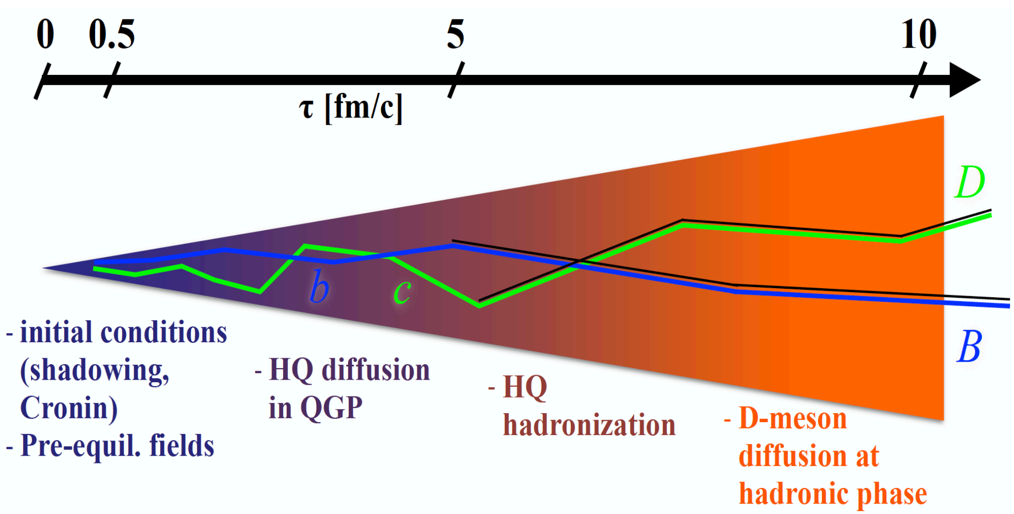
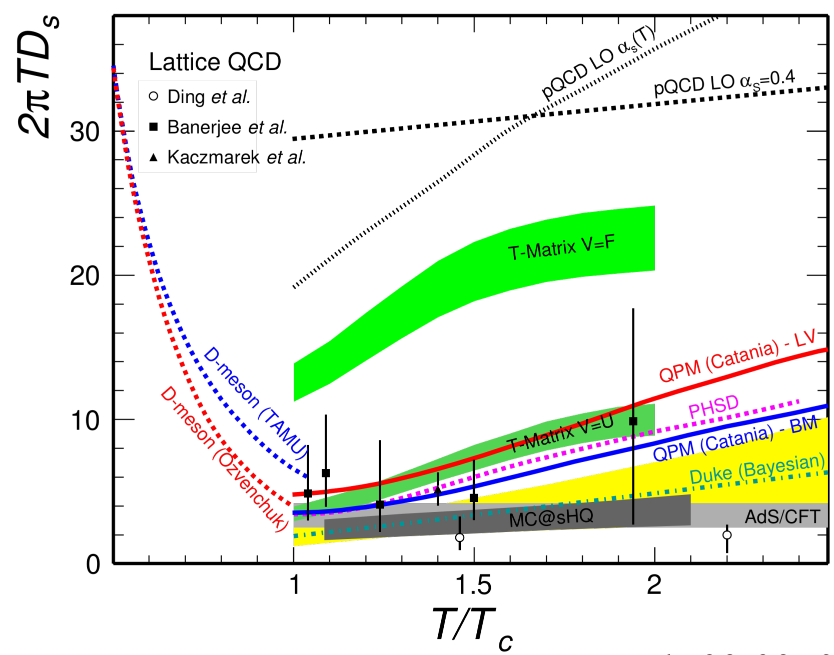
Introduction

Heavy quarks: $m_{c/b} >> \Lambda_{QCD}, T_{QGP(RHIC)}$

- Produced early in heavy-ion collisions through hard scatterings
- Experience the whole evolution of the system
  → good probe of medium properties, e.g. transport parameters





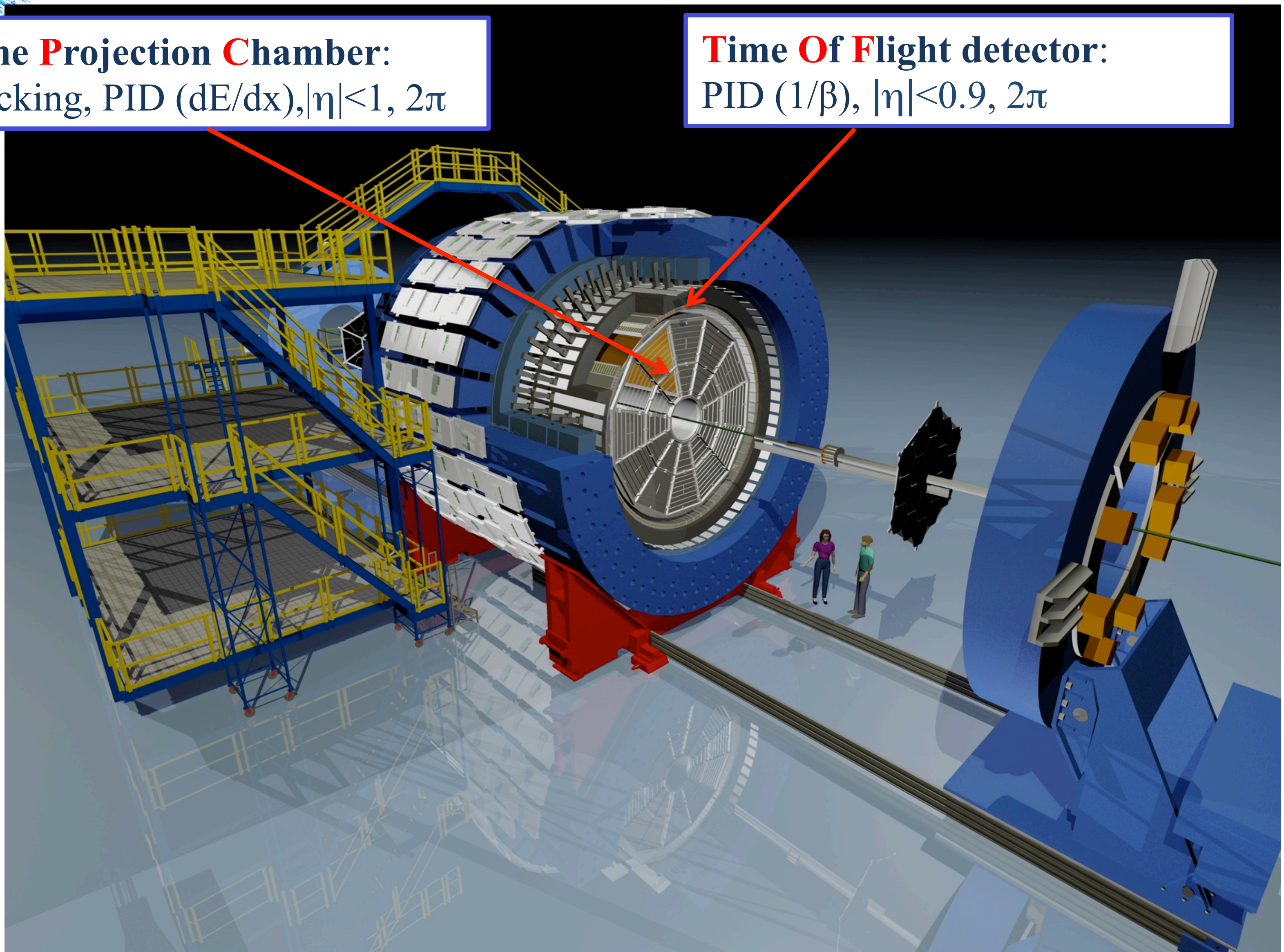
arXiv: 1502.02730

Contents

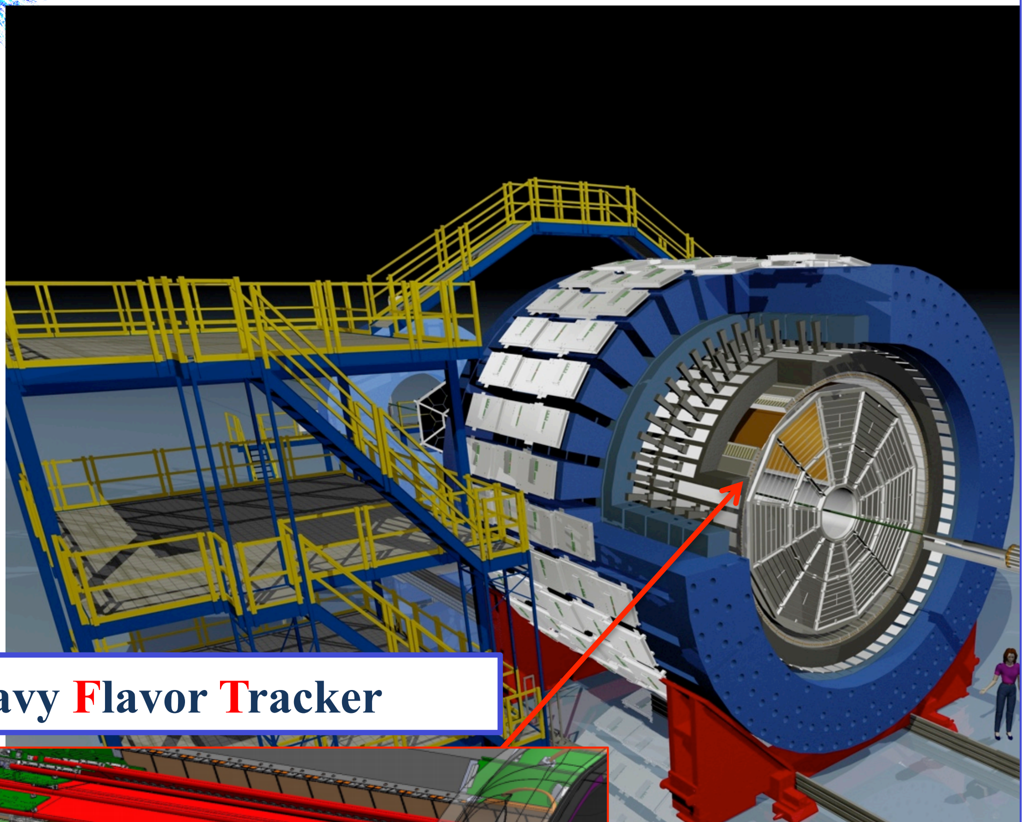
- In medium energy loss
  D^0 R_{AA}, R_{CP}
- Hadronization
  Λ_c, D_s
- Charm conservation
  Total charm cross-section
- Possible medium modification of spectral function
  $D^{*+/-}$
- Mass dependence of energy loss
  $B \rightarrow (J/\psi, D^0, e)$

- Probe the longitudinal profile and electromagnetic field
  D^0 v_1
- Transport coefficients
  D^0 v_2

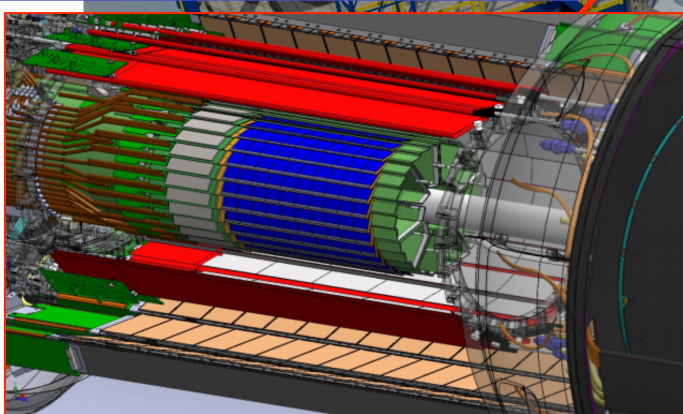
STAR Detector

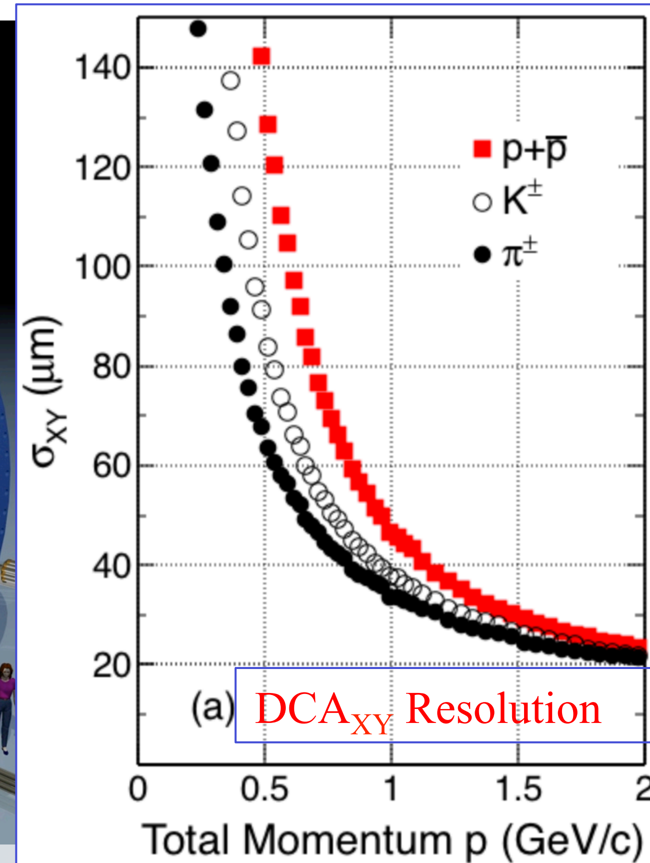


Heavy Flavor Tracker



Heavy Flavor Tracker



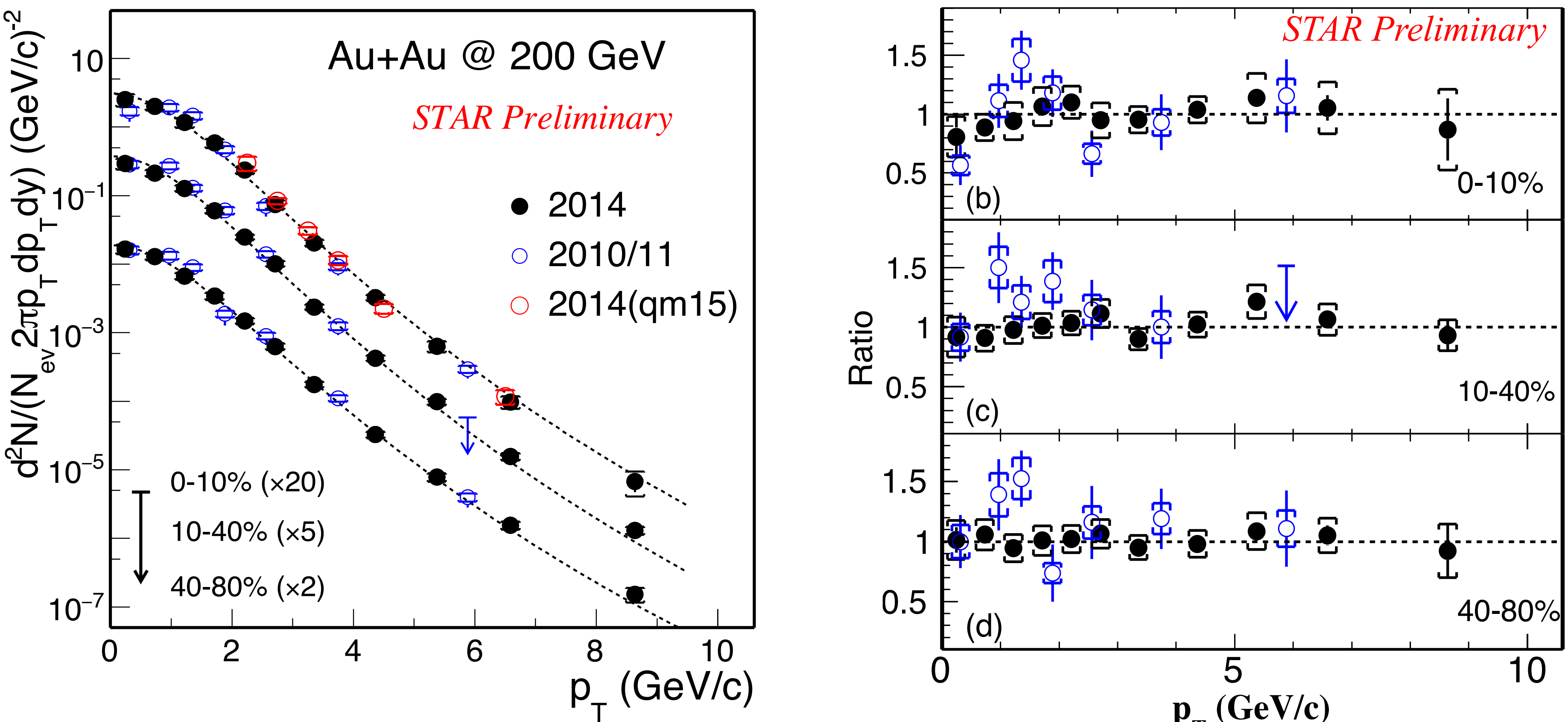


HFT:

- Silicon Strip Detector: r ~22 cm
- Intermediate Silicon Tracker: r ~14 cm
- PIXEL detector: r ~2.8 & 8 cm, MAPS, 20.7x20.7 μm^2, 0.4%X_0(2016) thick, air-cooled

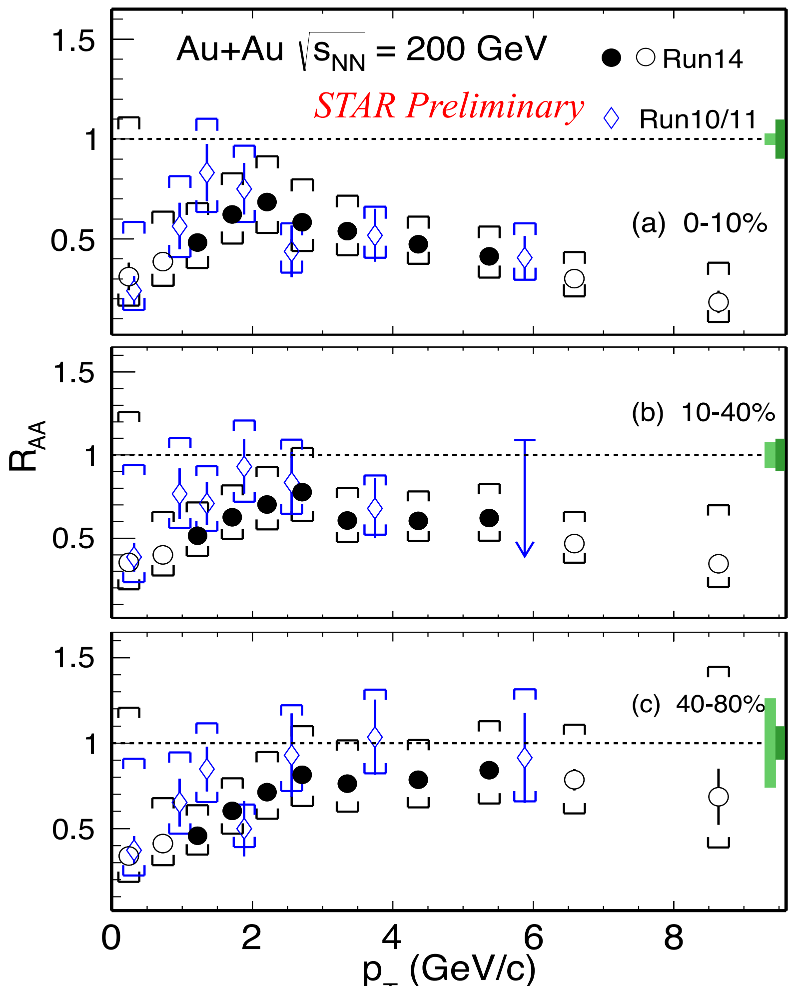
D^0 p_T Spectra

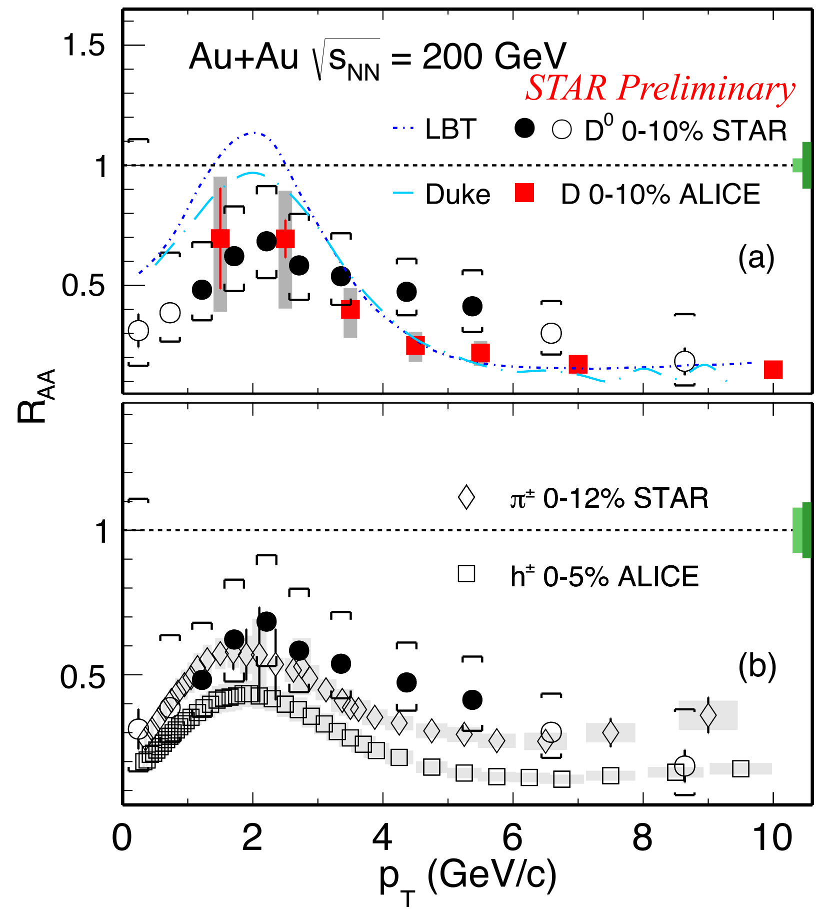
- Precise measurements of D^0 spectra extended to low p_T and non-central collisions with HFT from 2014 data
- Results consistent with the re-analyzed 2010/11 TPC analysis



D^0 R_{AA}

- $R_{AA} < 1$ in the 0-10% centrality interval for all p_T
- Suppression at high p_T increases towards more central collisions
- Similar to D-mesons at LHC and high-p_T pions at RHIC

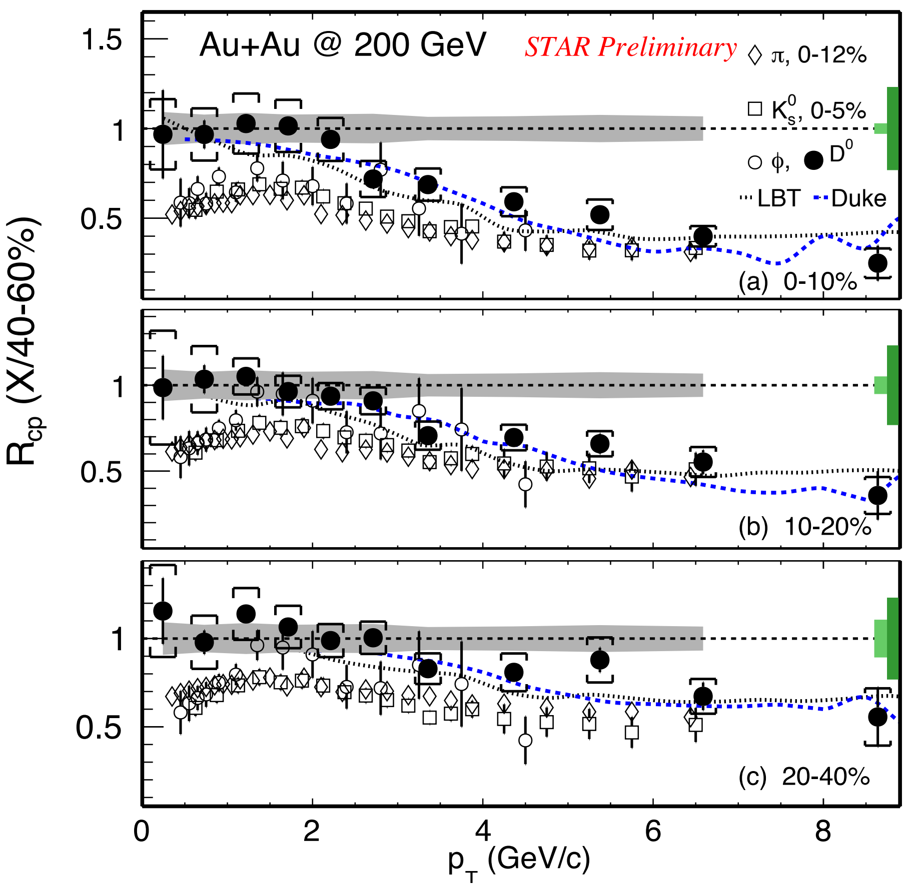


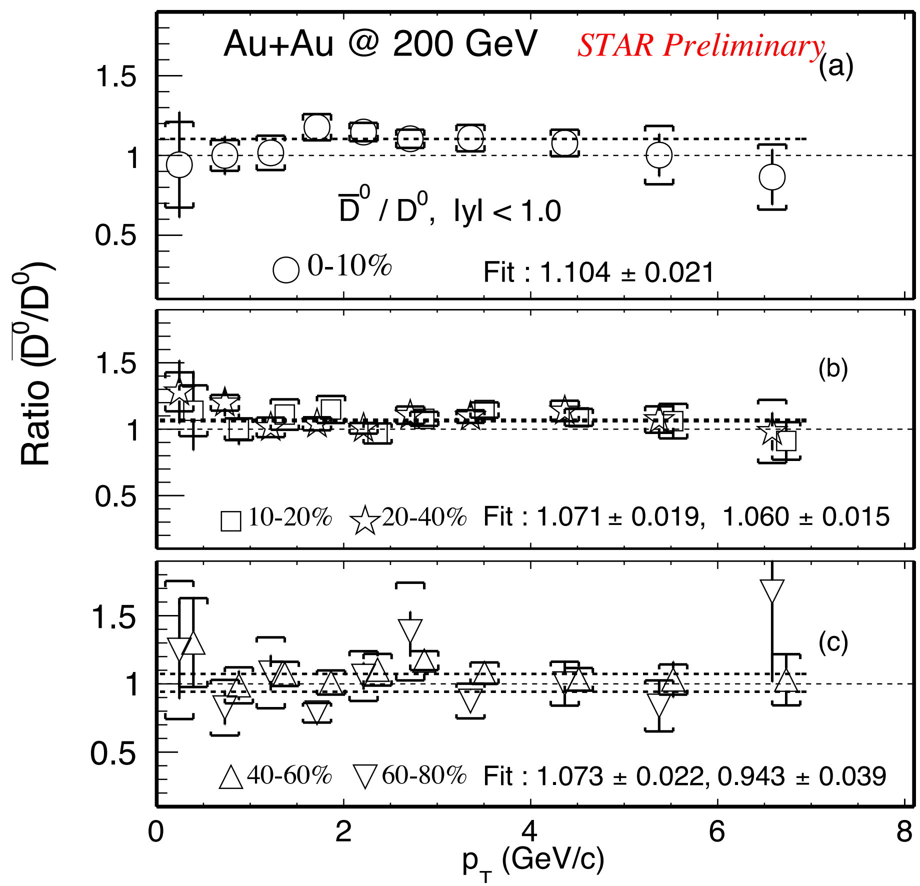


STAR:Phys. Lett. B 655 (2007) 104
ALICE: JHEP 03 (2016) 081
LBT: Phys. Rev. C94, 014909 (2016)+private comm.
DUKE: PRC 92 (2015) 024907+private comm.

D^0 R_{CP} and $\overline{D}^0/D^0$ Ratio

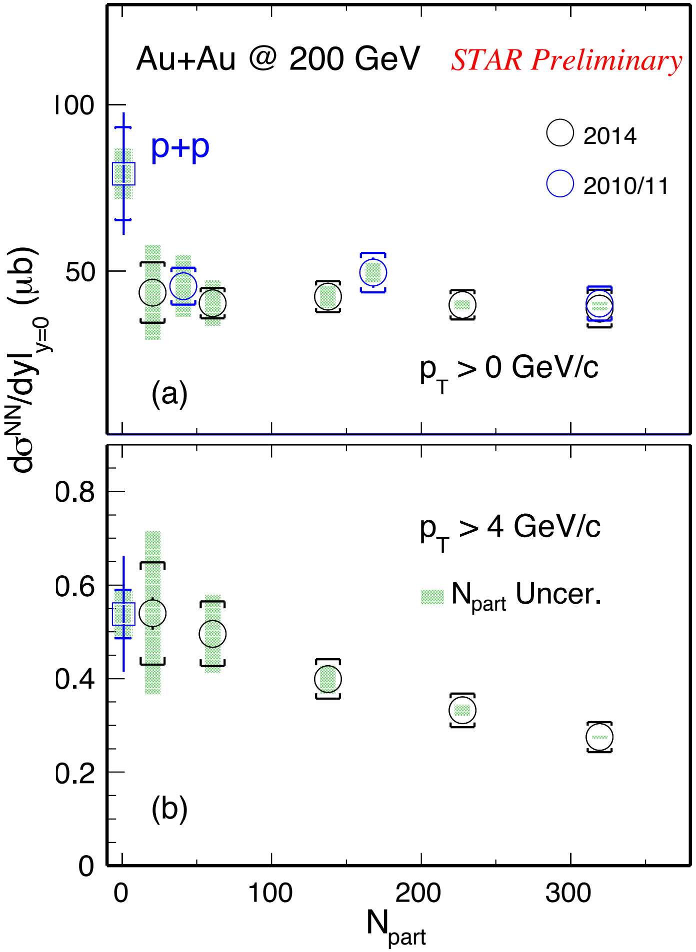
- Significant suppression at high p_T .
- Reasonable agreement with theoretical calculations
- $\overline{D}^0/D^0$ ratio is larger than 1.

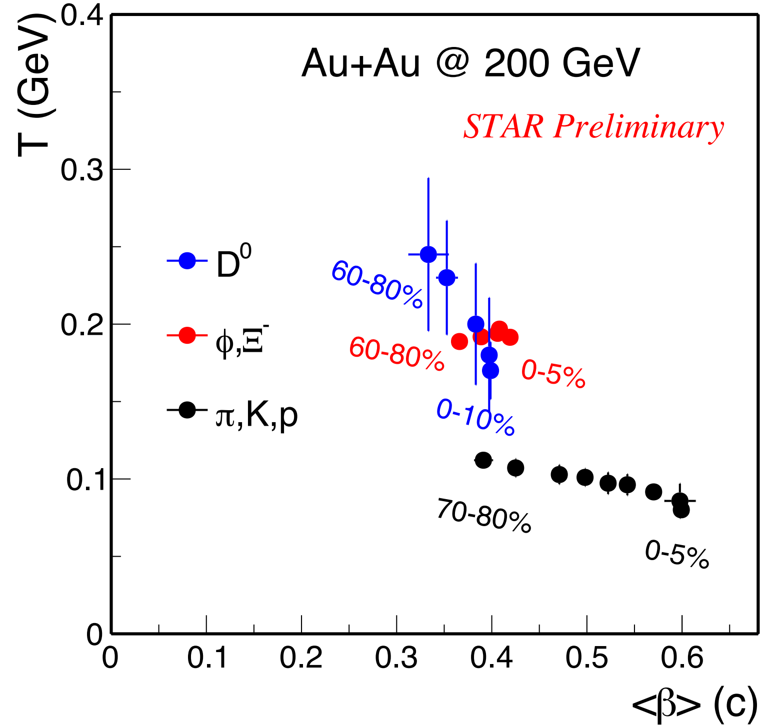




D^0 Cross-section and Blast Wave Fit

- Total D^0 cross-section is nearly independent of centrality, and smaller than in p+p. However, for $p_T > 4$ GeV/c it decreases with centrality.
- Blast Wave fits ($p_T < 5$ GeV/c) : suggests earlier freeze-out of D^0

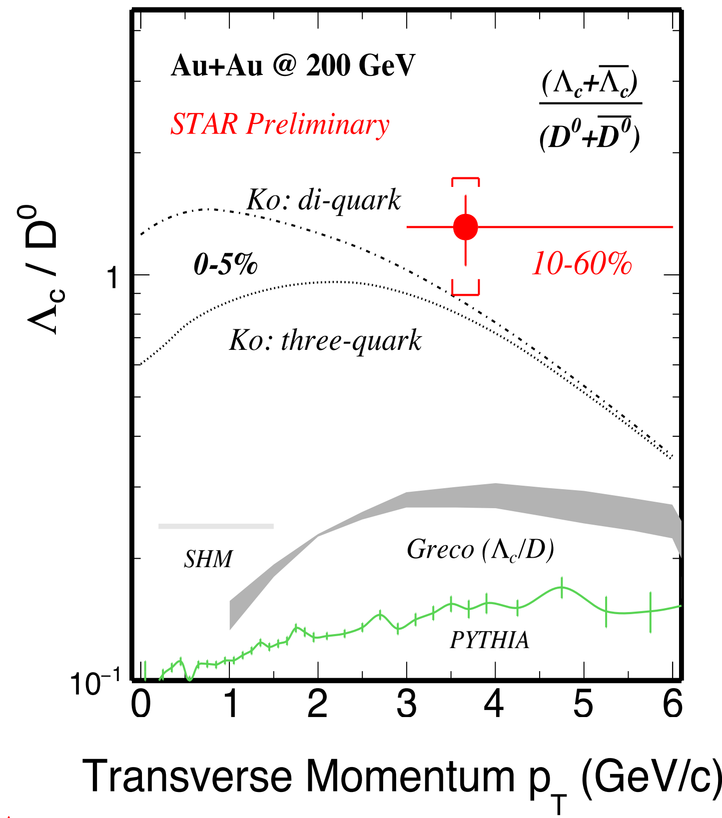


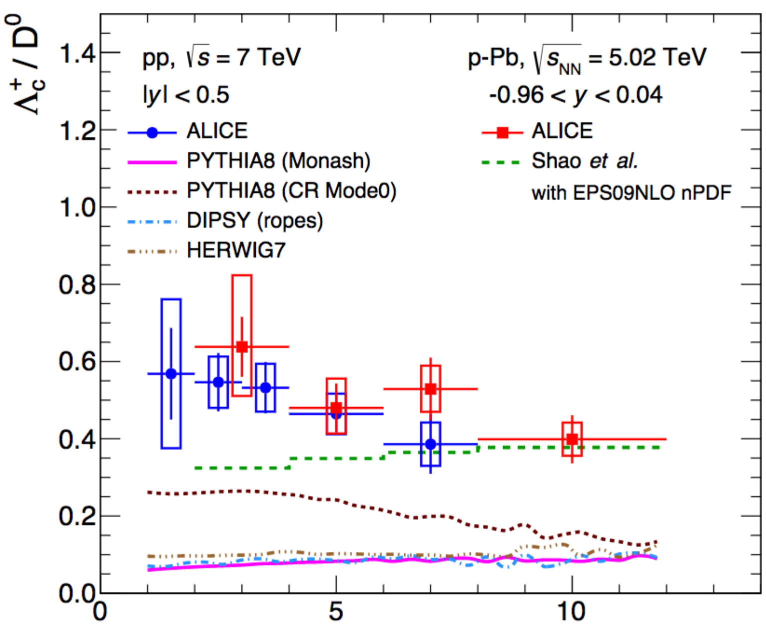


Λ_c and Heavy Quark Hadronization

- Strong enhancement of Λ_c/D^0 ratio seen in Au+Au collisions.
- Enhancement predicted from coalescence hadronization.
- Enhancements relative to PYTHIA also seen in p+p and p+Pb collisions at LHC.

QM17



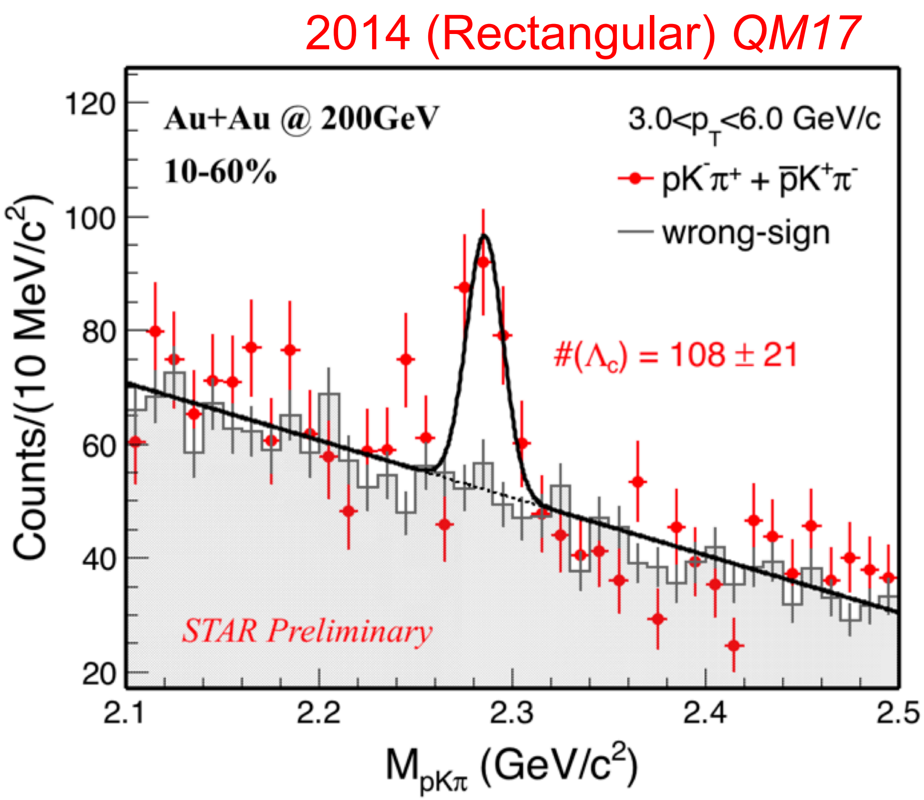


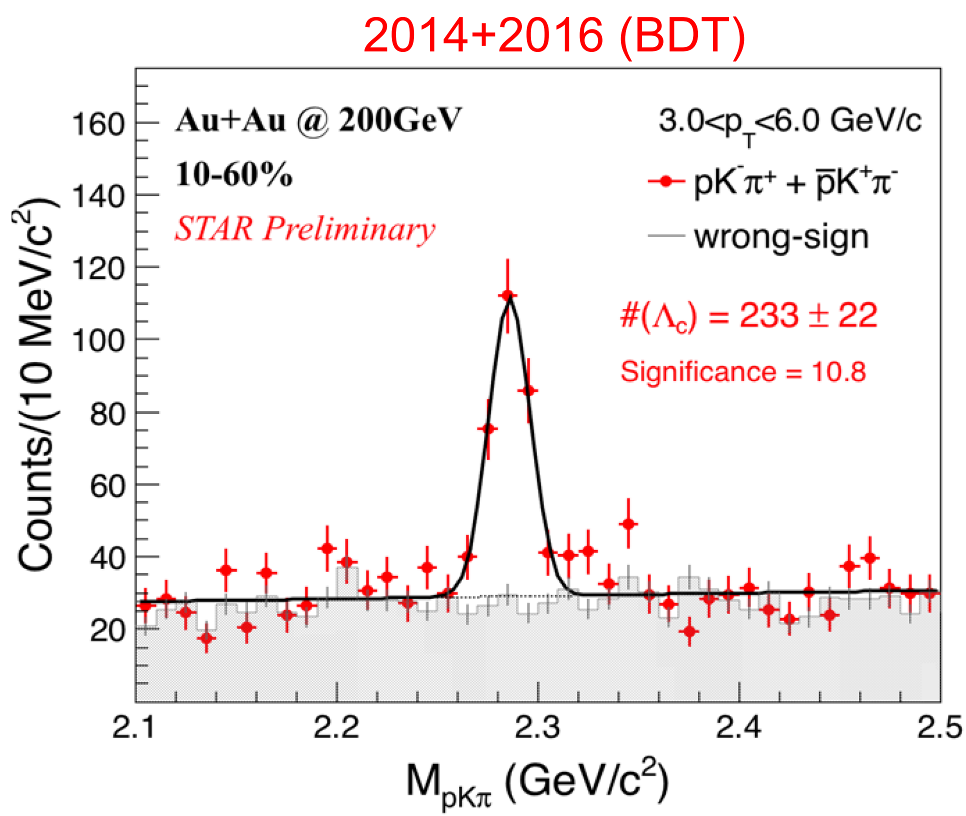
Λ_c/D^0 in A+A
p_T and centrality dependence?

Ko: PRC 79 (2009) 044905. Greco: PRD 90 (2014) 054018
SHM: PRC 79 (2009) 044905. ALICE: arXiv:1712.09581

Λ_c Reconstruction

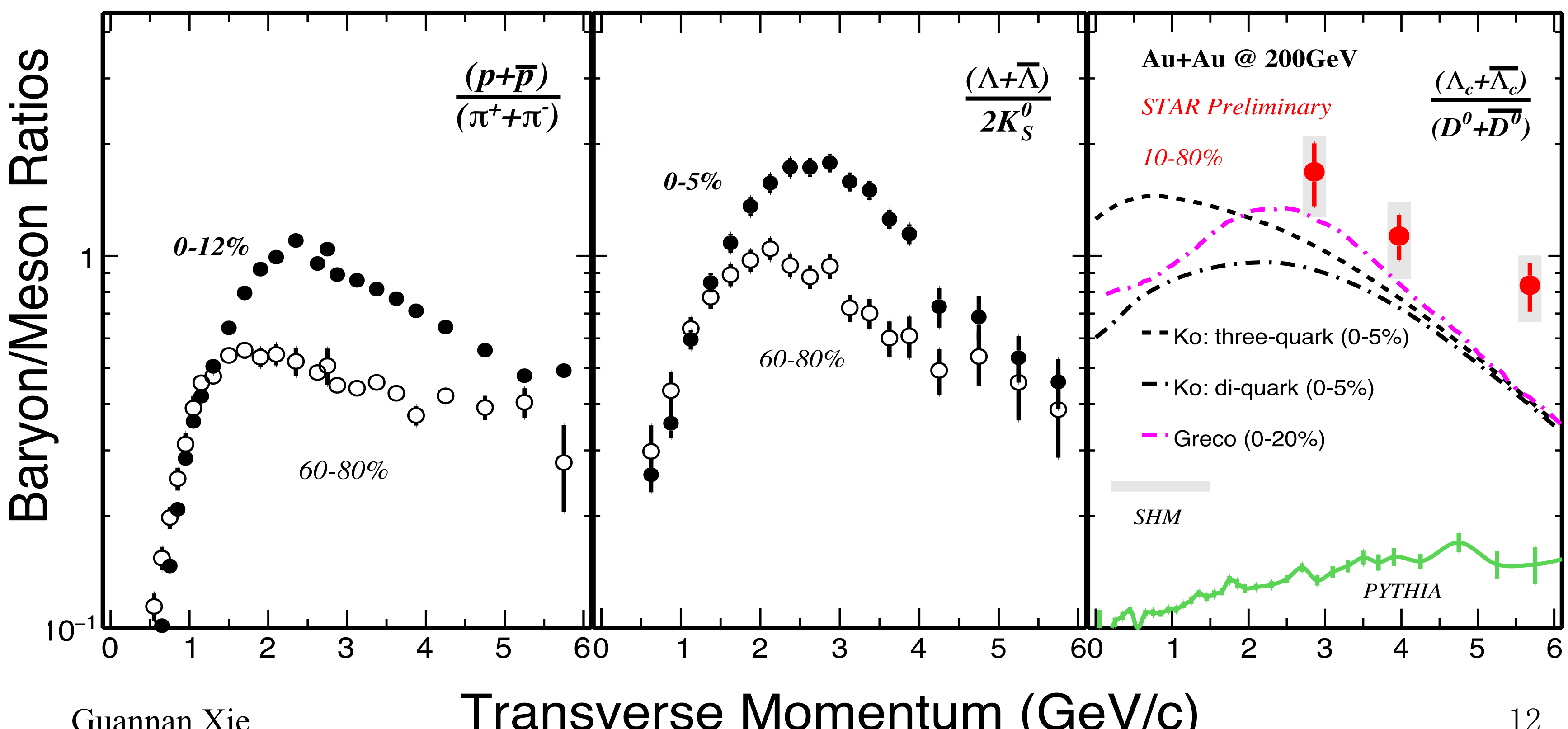
- More than 50% improvement in signal significance with TMVA BDT
- Also new data from 2016
  → Effectively 4x more data





Λ_c/D^0 : p_T Dependence

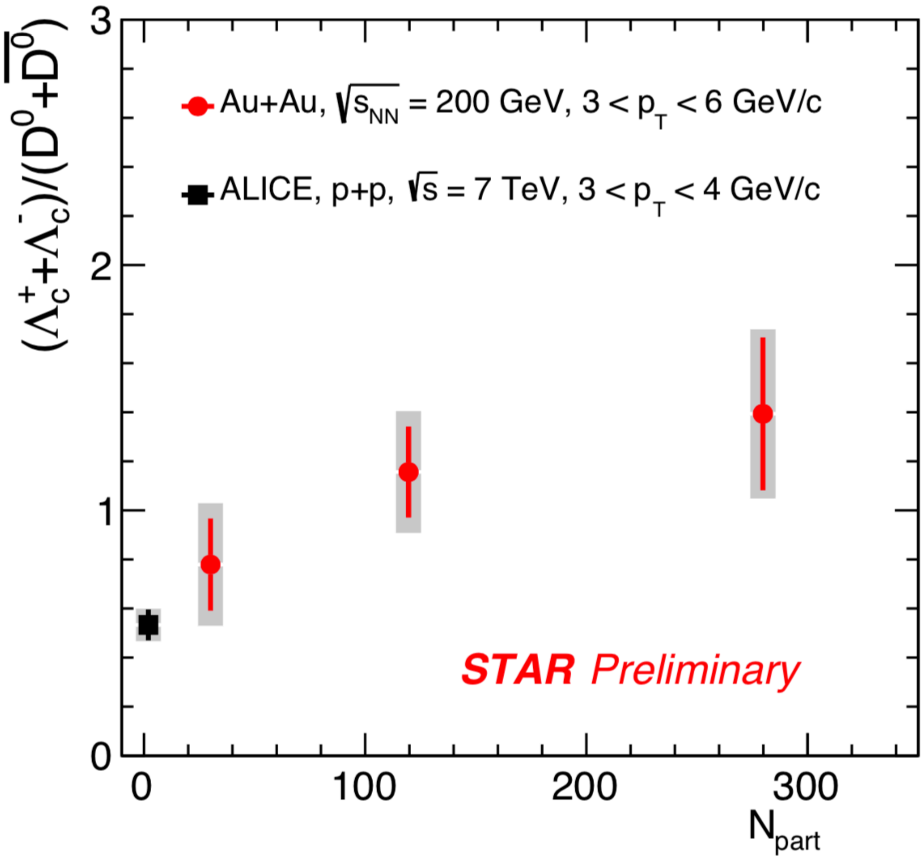
- Significant enhancement of Λ_c/D^0 compared to PYTHIA/fragmentation baseline
- The Λ_c/D^0 ratio is comparable with light flavor baryon-to-meson ratios
- Consistent with charm quark hadronization via coalescence
  -- higher than model predictions, particularly at higher p_T



Ko: PRC 79 (2009) 044905 Greco: Eur.Phys.J.C (2018) 78:348
SHM: PRC 79 (2009) 044905 ALICE: arXiv:1712.09581

Λ_c/D^0 : Centrality Dependence

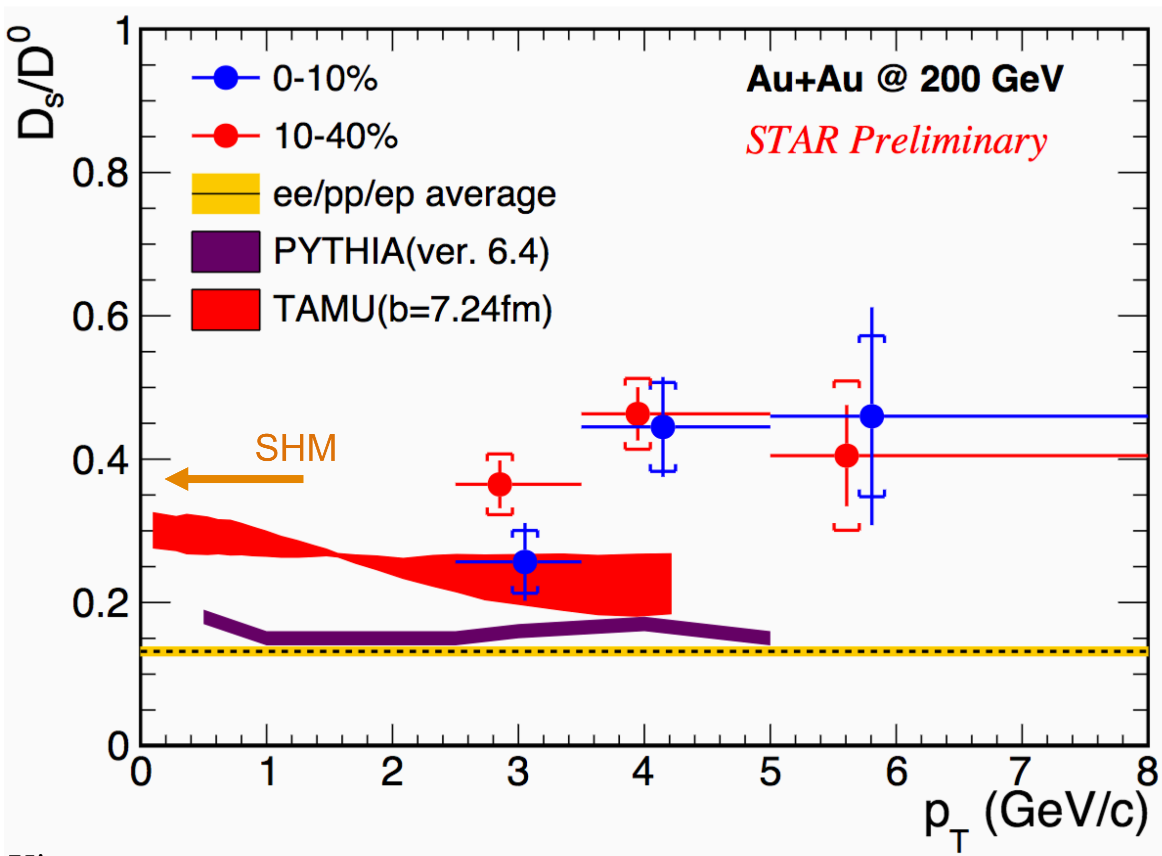
- Λ_c/D^0 ratio increases from peripheral to central collisions, indicative of hot medium effects
- Ratio for peripheral Au+Au comparable with p+p value at 7 TeV



ALICE: arXiv:1712.09581

D_s/D^0 Enhancement

- Strong D_s/D^0 enhancement observed in central A+A collisions w.r.t fragmentation baseline
  - Strangeness enhancement and coalescence hadronization
- Enhancement is larger than model predictions, particularly at higher p_T



ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, 397 (2016)
TAMU: H. Min et al. PRL 110, 112301 (2013)
SHM: A. Andronic et al., PLB 571 (2003) 36

Total Charm Cross-section

- Total charm cross-section is estimated from the various charm hadron measurements

-- D^0 yields are measured down to zero p_T
-- For $D^{+/-}$ and D_s, levy fits to measured spectra are used for extrapolation.
-- For Λ_c, three model fits to data are used and differences are included in systematics

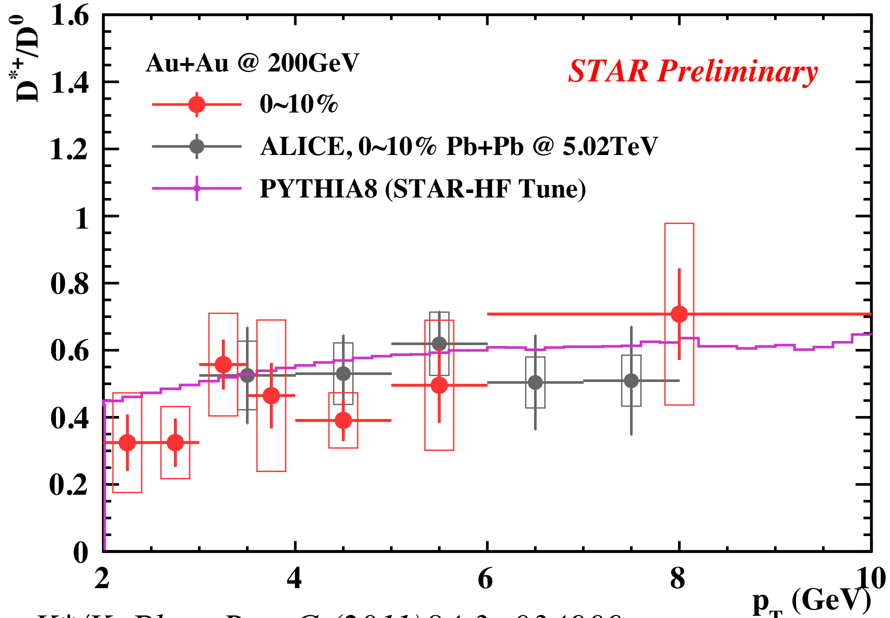
Charm Hadron		Cross Section dσ/dy (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

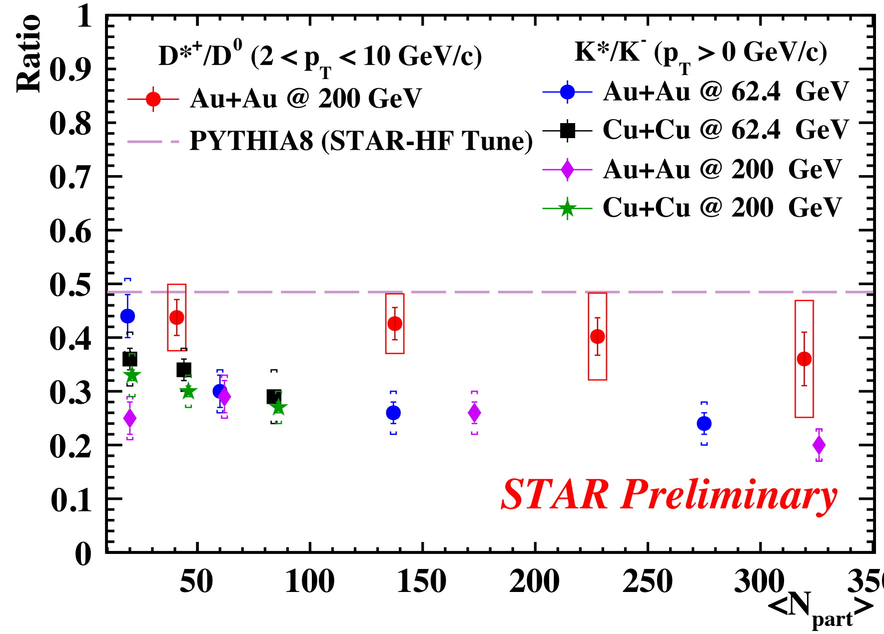
*** derived using Λ_c^+ / D^0 ratio in 10-80%**

- Total charm cross-section is consistent with p+p value within uncertainties, but redistributed

D^{*+}/D^0 Ratio in Au+Au Collisions

- Possible hot medium effects :
  - D^{*+} life time could become shorter in hot medium
  - Re-scattering can lead to a yield loss
- D^{*+}/D^0 ratio in Au+Au collisions at 200 GeV is consistent with PYTHIA and with ALICE data at higher p_T.
- Ratio of the integrated yields shows no strong centrality dependence



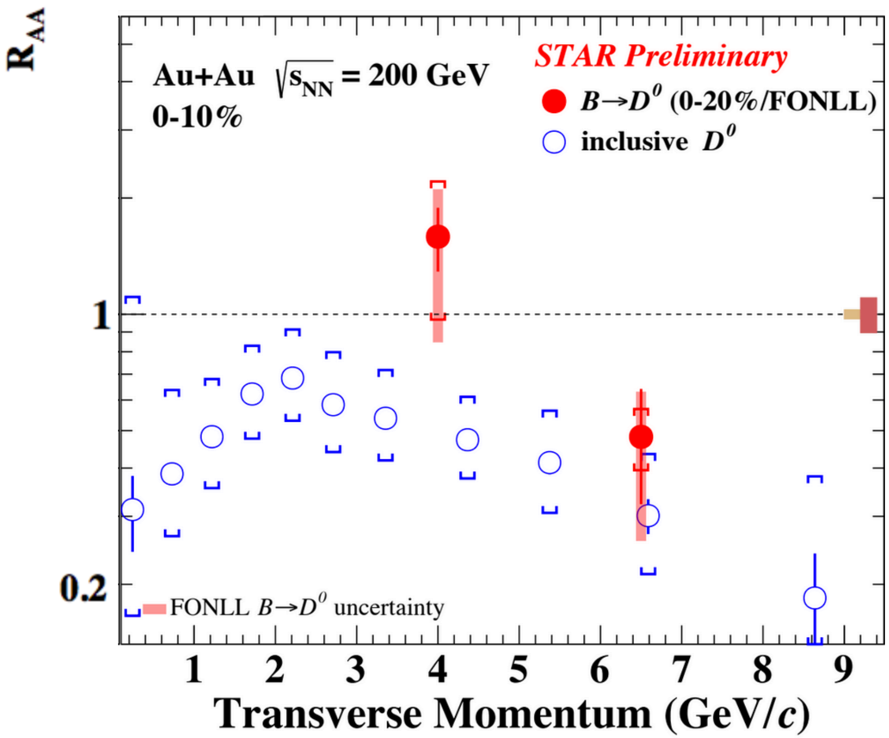


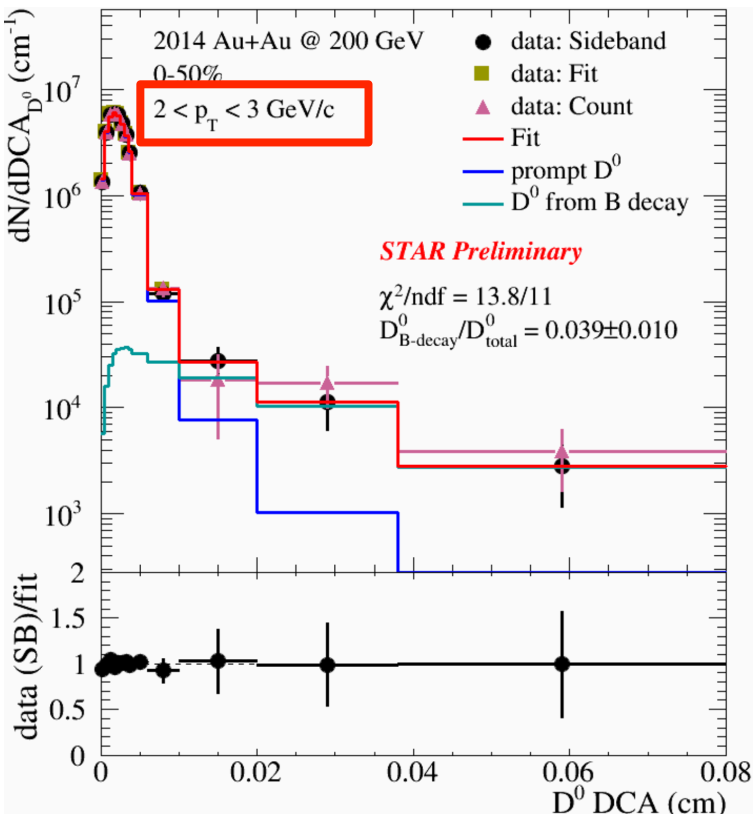
K/K, Phys. Rev. C (2011)84.3: 034909.*
ALICE, Collaboration. arXiv:1804.09083.

Non-prompt D^0

- Strong interaction of charm with the medium. How about bottom?
- R_{AA} of non-prompt D^0 extracted from the measured non-prompt fraction
- Improved signal significance for non-prompt D^0 fraction using BDT.

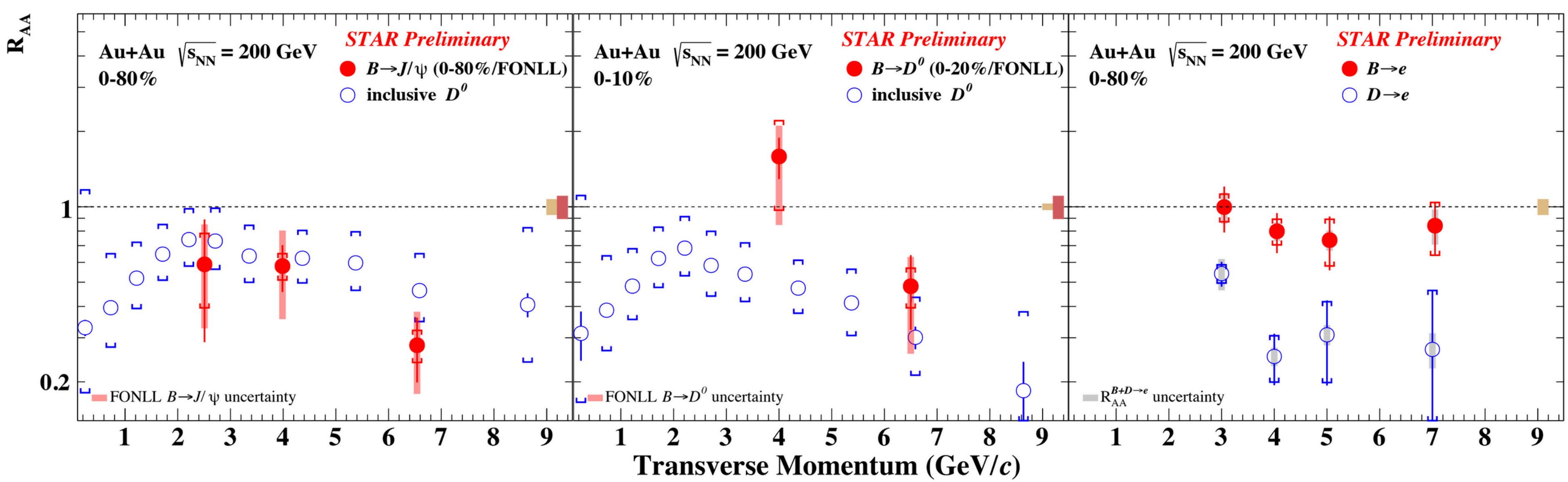
  New result down to low p_T with 2014+2016 data on the way





B Study from Non-prompt J/ψ & D^0 & e

- Strong suppression for $B \rightarrow J/\psi$ and D^0 at high p_T.
- Indication of less suppression for $B \rightarrow e$ than $D \rightarrow e$ (~2 σ): consistent with $\Delta E_c > \Delta E_b$
- Measurements with improved precision are on the way

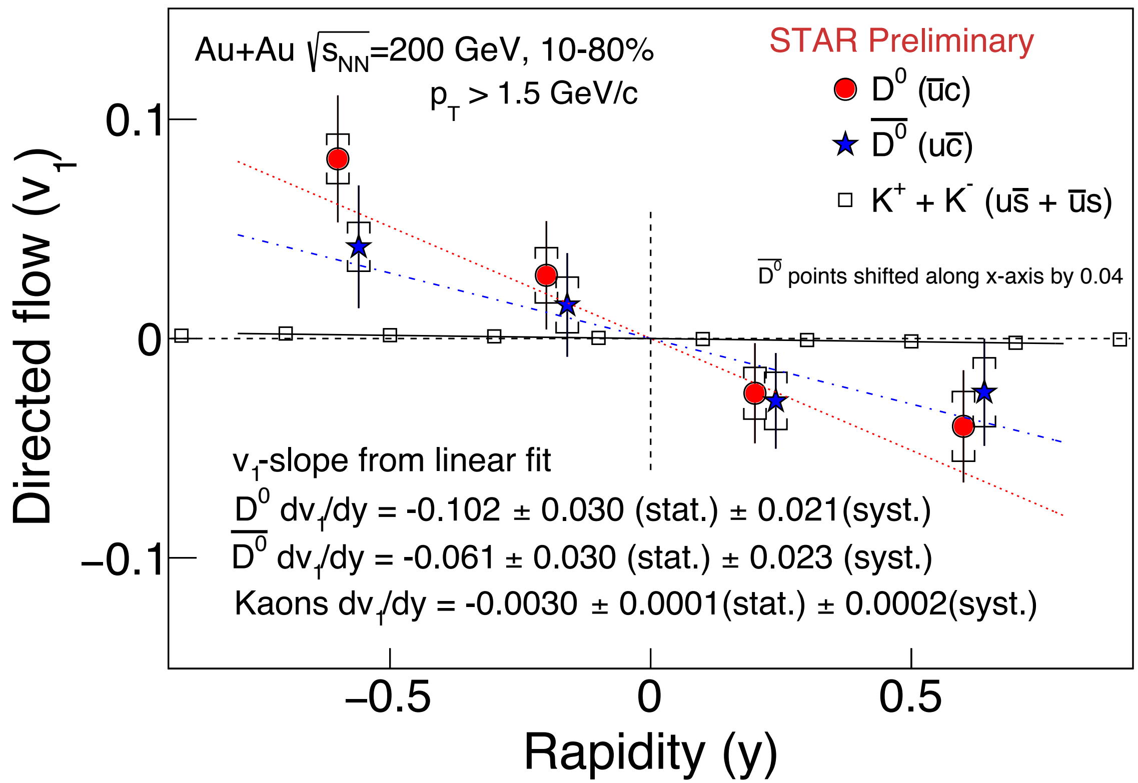


Note: R_{AA} references (data vs. theory) are different for these comparisons.
The decay kinematics needs to be unfolded for different channels.

D^0 Directed Flow (v_1)

- Charm and anti-charm quarks can be deflected differently by the initial EM field → difference between D^0 and $\overline{D^0}$ v_1 sensitive to EM field
- Charm quarks interact with bulk medium → D^0 v_1 sensitive to the initial tilt of the source (bulk)
- First observation of non-zero (negative) $D^0(\overline{D^0})$ v_1 slope
- $D^0(\overline{D^0})$ v_1-slope much larger than that of kaons

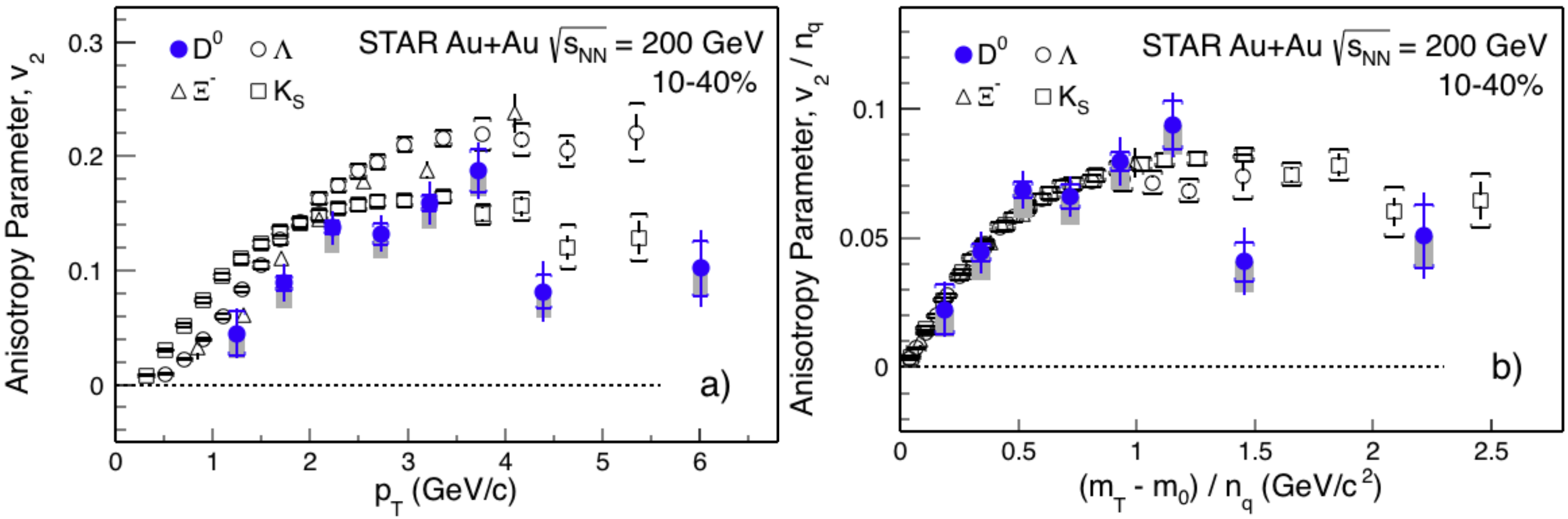
2014+2016



D^0 Elliptic Flow (v_2)

- Published D^0 v_2 from data taken during 2014
- Clear mass ordering for p_T < 2 GeV/c
- Follows NCQ-scaling in mid-central (10 - 40%) collisions

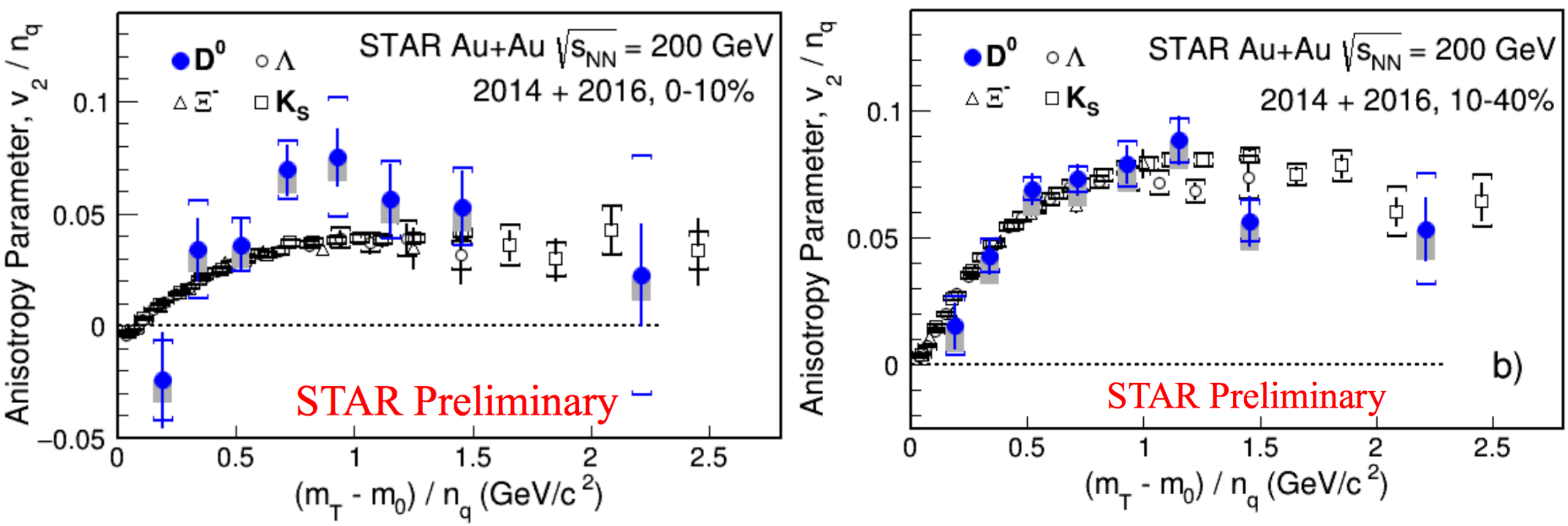
Phys Rev. Lett. 118, 212301 (2017)



D^0 Elliptic Flow (v_2)

- D^0 v_2 measurement extended to 0-10% centrality with combined data from 2014 and 2016 runs
- NCQ-scaling test with improved precision
- Charm quarks gain significant flow!

2014+2016

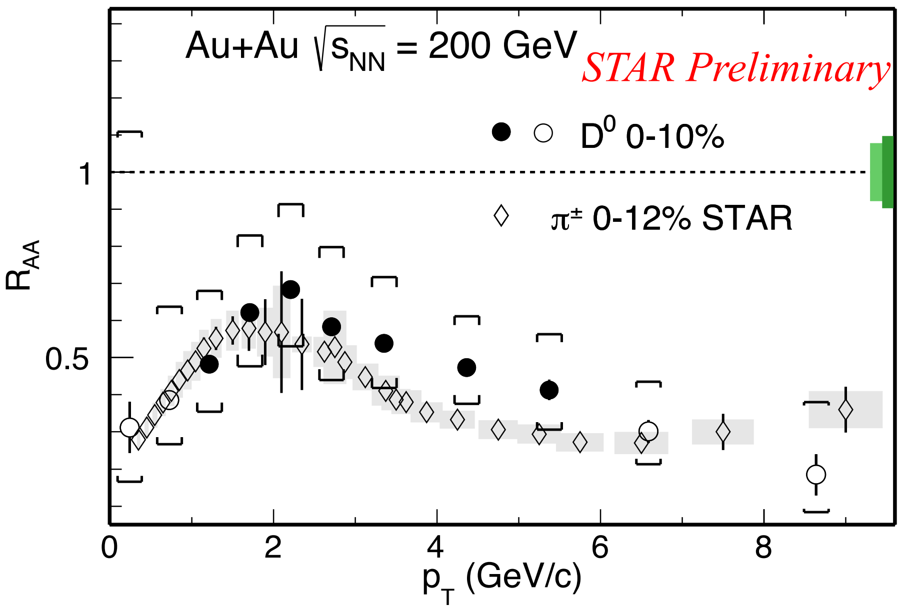


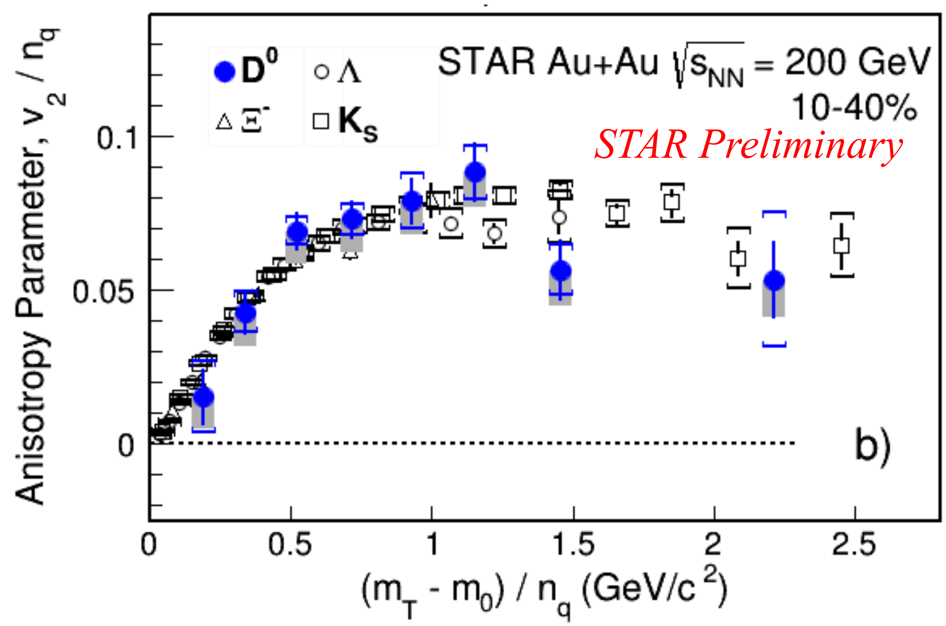
Summary

- Strong modification of charm hadron spectra and hadrochemistry in A+A collisions. (D^0 R_{AA} & R_{cp}, D_s/D^0, Λ_c/D^0, D^0 v_2, D^0 v_1).
  -- total charm quark cross-section conserved
  -- substantial energy loss & coalescence hadronization
  -- gain significant flow & may have achieved thermal equilibrium in the medium (D^0 v_2)
  -- first observation of non-zero directed flow (v_1) for D^0.

- Strong energy loss at high p_T for $B \rightarrow J/\psi$, *and* $B \rightarrow D^0$ measurements. Indication of less energy loss for bottom ($B \rightarrow e$), and measurement with better precision on the way.

Summary II – Charm / Bottom





$R_{AA}(D^0) \sim R_{AA}(\pi)$	- lose significant energy
$v_2(D^0) \sim v_2(h)$ vs. m_T	- gain significant flow

Next

Experimental : precision measurement of bottom

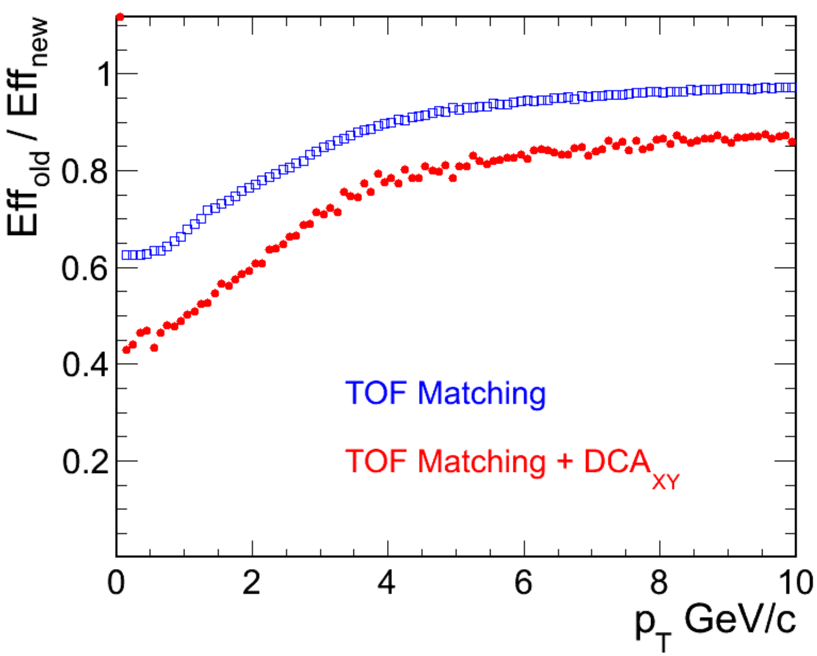
Theoretical : converge on value of transport parameters

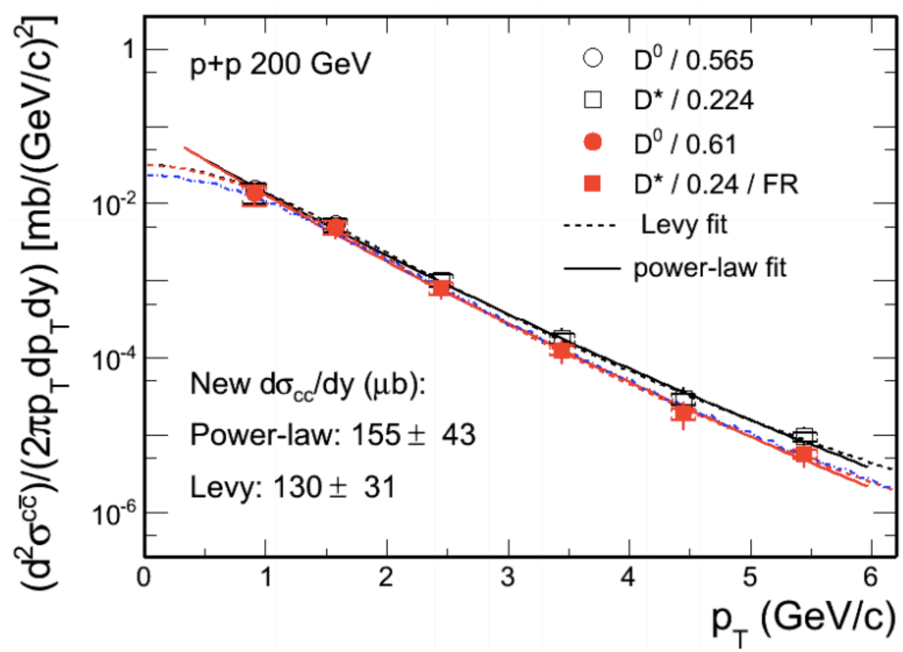
Back up

D^0 in AuAu (2010/2011 TPC Analysis) - I
Erratum: PRL 113 (2014) 142301

1. Two mistakes were discovered in calculating TOF related efficiency corrections
   - Hybrid PID: algorithm inconsistently implemented in data analysis vs. efficiency calculation
   - a DCA_{xy} cut efficiency was included in the correction two times
2. p+p measurement: no issue discovered, but the p+p D^0 baseline used for R_{AA} is updated with latest knowledge of charm frag. ratios
   - considering the p_T dependence of D^*/D^0 frag. ratio
   - latest world average of c->D^0 and c->D^* frag. ratios

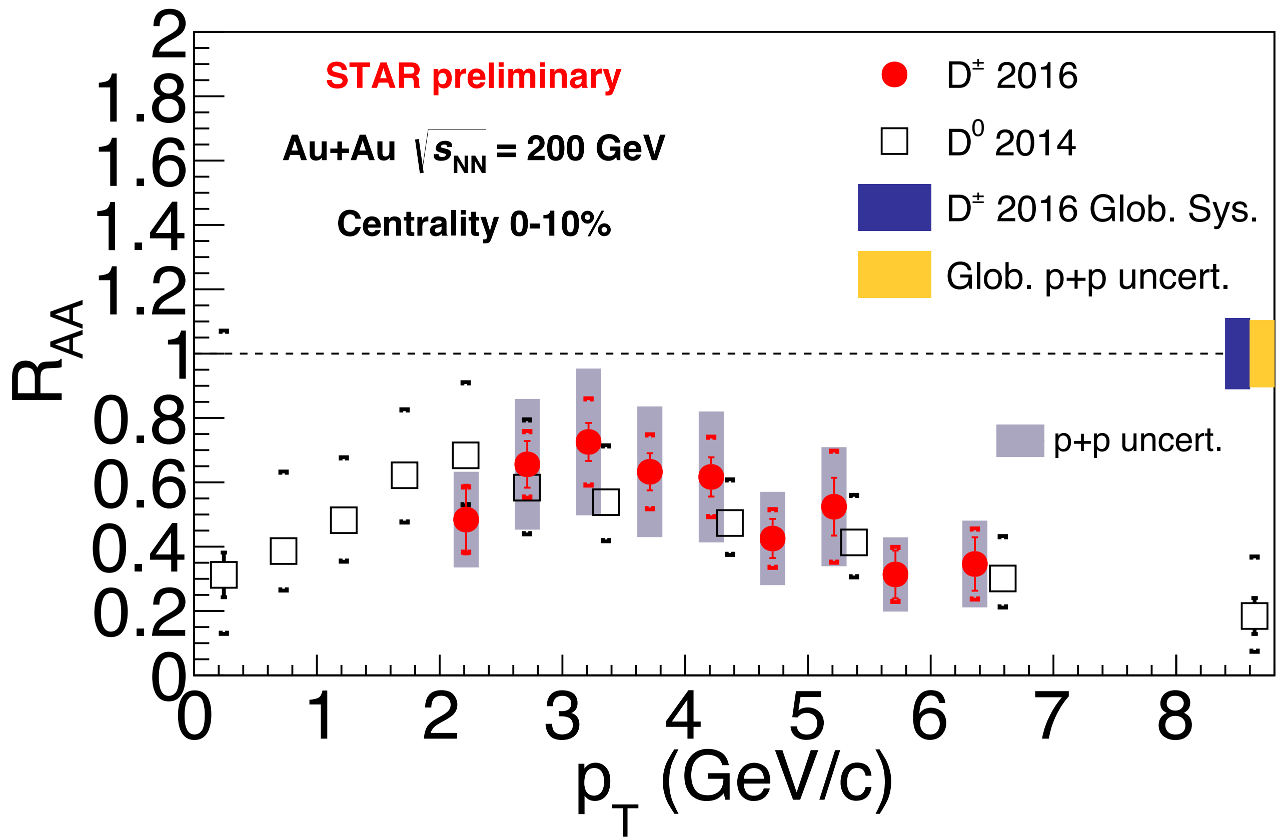
(D^0 at p_T<2 GeV/c + D^* at 2-6 GeV/c, *PRD 86 (2012) 072012*)





$D^{+/-}$ R_{AA}

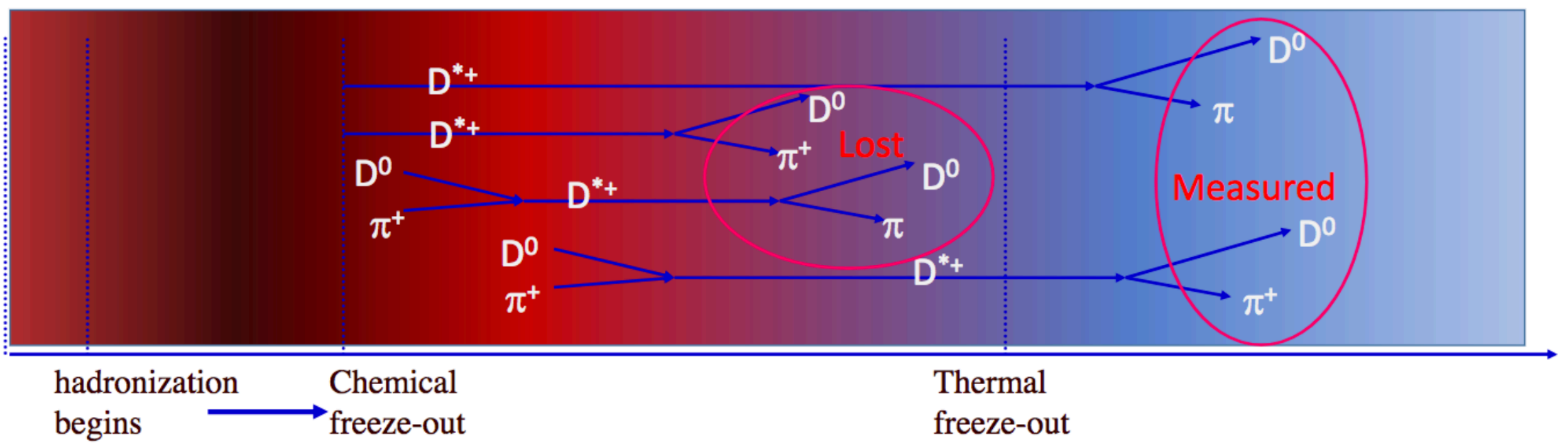
- Similar suppression for D^0 and $D^{+/-}$
- Spectra measurement was important for the total charm cross-section



D^{*+} Production in Au+Au Collisions

- D^{*+} feeds down to D^0 yields $D^{*+} \rightarrow D^0 + \pi^+_{soft}$
- Hot medium effects :

  - D^{*+} life time could become shorter in hot medium
  - Re-scattering can lead to loss of yield



Phys. Rev. C (2018)97, 034918. Phys. Rev. C (2011)84, 034909

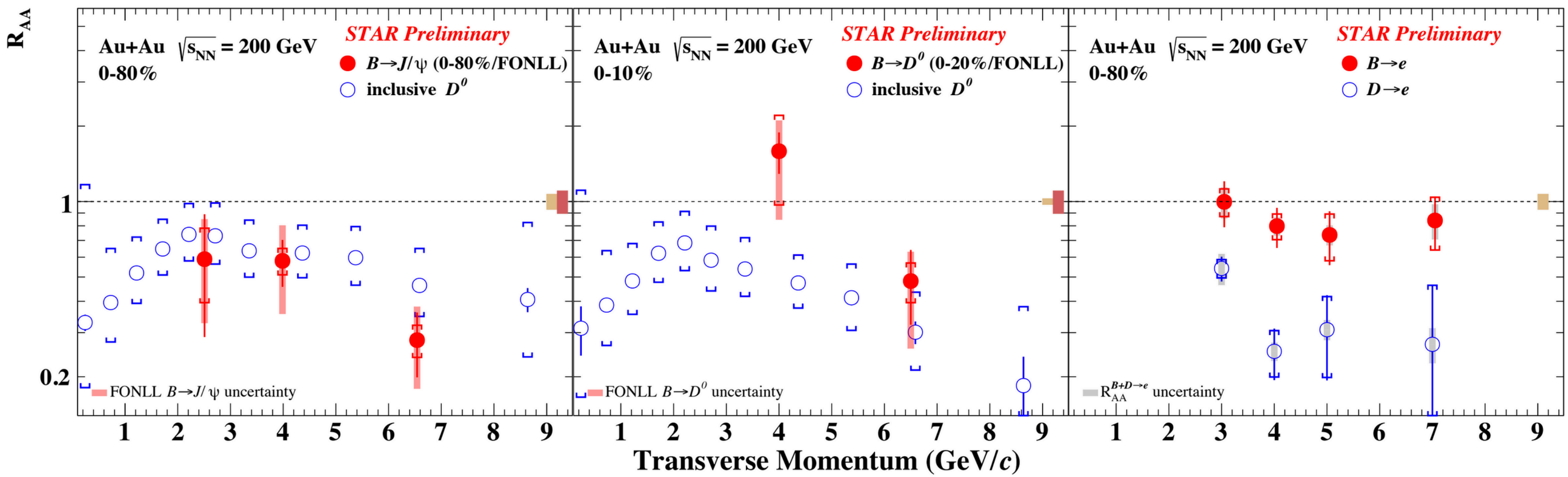
B Study from Non-prompt J/ψ & D^0 & e

$$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(data)}{f_{p+p}^{B\to J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data)$$

$$R_{AA}^{B\to D^0} = \frac{1}{<N_{coll}>} \frac{f_{Au+Au}^{B\to D^0} \times dN_{Au+Au}^{incl.\ D^0}/dp_T}{dN_{FONLL}^{B\to D^0}/dp_T}$$

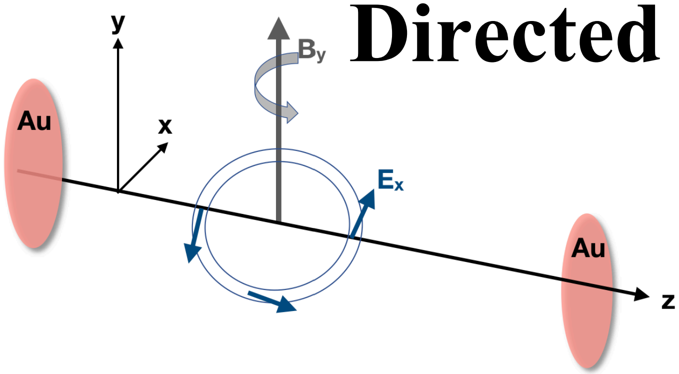
$$R_{AA}^{B\to e} = \frac{f_{Au+Au}^{B\to e}(data)}{f_{p+p}^{B\to e}(data)} R_{AA}^{inc.\ e}(data)$$

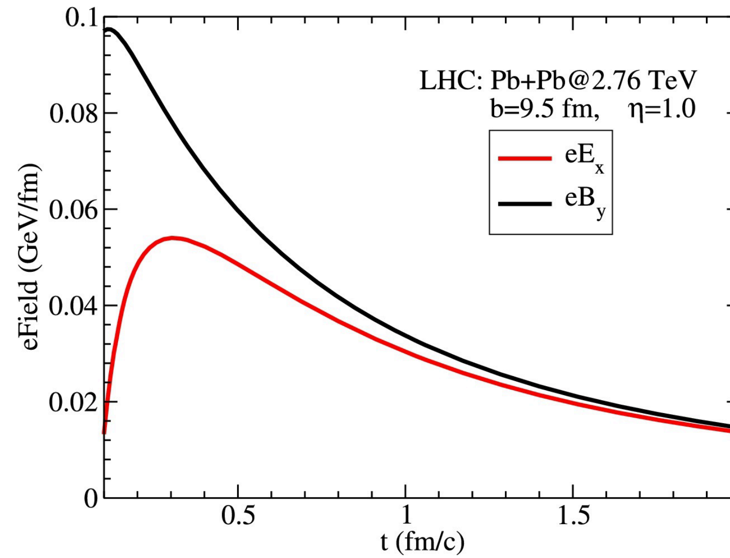
$$R_{AA}^{D\to e} = \frac{1-f_{Au+Au}^{B\to e}(data)}{1-f_{p+p}^{B\to e}(data)} R_{AA}^{inc.\ e}(data)$$



Note: R_{AA} references (data vs. theory) are different for different channels

Directed flow (v1) due to EM fields

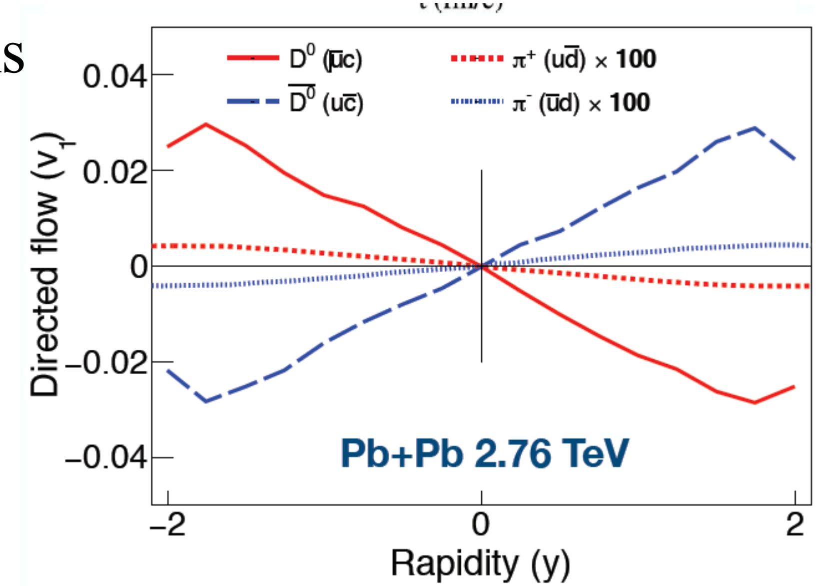




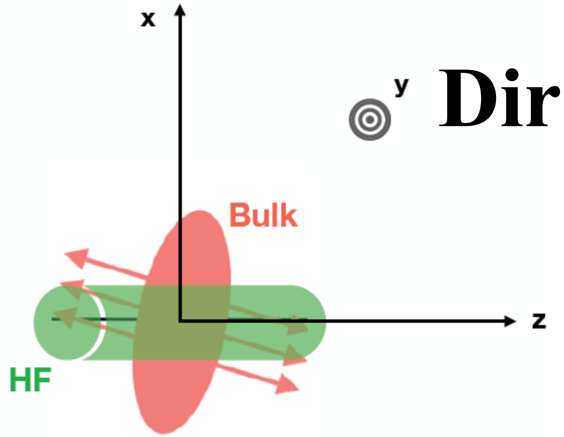
- The moving spectators can produce enormously large electromagnetic field ($eB \sim 10^{18}$ G at RHIC)

- Due to early production of heavy quarks ($\tau_{CQ} \sim 0.1$ fm/c) positive and negative charm quarks (CQs) can get deflected by the initial EM force

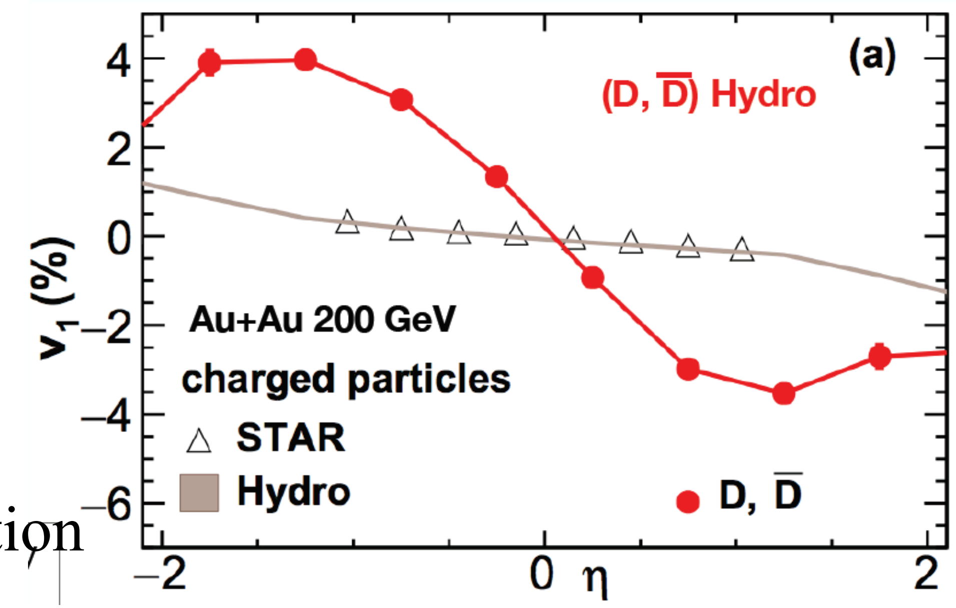
- D^0 and D^0 v_1 can offer insight into the early time EM fields



Das et. al., Phys Lett B 768, 260 (2017)



Directed flow (v1) due to hydro



Chatterjee, Bozek:
Phys Rev Lett 120, 192301 (2018)

- Heavy quarks are produced according to Ncoll density: symmetric in rapidity
- At non-zero rapidity, CQs production points are shifted from the bulk
- This can induce larger v_1 in CQs than light flavors
- Magnitude of CQ v_1 depends on the drag parameter used in this model

→ $(v_1\text{-slope})_{CQ} >> (v_1\text{-slope})_{LQ}$ CQs much more sensitive to the initial tilt than the charged hadrons